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Continued Measurement of Fault Creep in the San Francisco Bay Area and elsewhere in California

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Investigations undertaken

We designed a new low power creepmeter that we installed in four locations in the Coachella Valley, one in Parkfield, and one at Nyland Ranch near San Juan Bautista. In addition we devised a low power extended-range (4 m) creepmeter that we installed in Parkfield. We repaired the five Hayward Fault creepmeters and installed three of the new low power creepmeters as back-up systems to overcome telemetry/power failures that have occurred from time to time. We processed the past decade of data on the Hayward fault and posted it on the web. We also processed incoming data Hayward and San Andreas Fault creep data and Long Valley tilt data and placed this on the web. We captured a 15 mm creep event at San Jaun Bautista, the data from which are posted on the web as graphs and numbers. Finally we have developed a web page to present raw and processed data that produces daily, weekly or monthly data plots and numerical download capability - http://strike~sjg/creep.

New creepmeters

Several technological advances have occurred in the past decade that offer improved creepmeter performance. The most important of these permits low power operation of unattended creepmeters. We designed two systems. The first is based on an ONSET microstation ($250) that can record four 12 bit data streams for a year on 4 AA cells. With 500 Mb of memory it can record two channels (creep and temperature) each minute for a year. The other unit is a U12 data logger that can record displacement with 1 mm resolution for a year at a sample rate of once every 10 minutes. Both units can sample at higher (1 sample/sec) or slower rates (sample per day). The recording units switch on sensor power prior to gathering its data. A low-power LVDT (6 mA Schaevitz DC-SE) or a potentiometer (2 mA 10 kΩ) records fault displacement, but are powered off for most of the time. By this means we may operate a creepmeter for a year from alkaline c-cells. The detailed operation of these units can be found as a Schaevitz technical note (both Schaevitz and Onset have posted these applications) and in Bilham et al. (2204).

The linear range of each *DC-SE* LVDT is 25 mm, but we find that this is bracketed by two non-linear regions that if used can extend the range by a further 25%. We use this range by calibrating the assembled operating system with a precision micrometer, using as output the voltage indicated by the data logger. The resulting range of the creepmeter is thus 32 mm with a resolution of 6 µm. Instruments based on the *Schaevitz DCSE* range of transducers (which have a rise time of less than 5 ms) can be arranged to record a factor of 2 smaller range or x2, x4, or x6 increased ranges with corresponding increased or reduced sensitivity. We found no other LVDTs had a sufficiently short rise time to exploit the 10 ms pre-recording "on-command" of the *Onset microstation*. The *U12* data logger based design switches power to a multiturn 10kΩ potentiometer linked to a constant tension spring motor removed from a 10 m tape measure. A 30 cm circumference wheel attached to the shaft permits a displacement sensitivity of 1 mm over a range of ≈3 m (Bilham et al. 2004).

We undertook a series of tests on currently available length standard materials (Table 1). Our preferred material is a graphite rod that comes in 10 foot lengths and is connected together by an epoxied stainless-steel crimp or a stainless-steel compression fitting. Invar, with a density four times higher is next, but this requires preparation using tapped ends and stainless grub screws. Glass or quartz fibers can be obtained as continuous lengths but are unpleasant to handle and install. We note that the thermal properties of all these potential materials are smaller than the thermal properties of the ground. A 10 m length of graphite expands ≈5 µm per degree, roughly the least count resolution of our recording package. The creep signal, therefore, is dominated in many of our installations by thermoelastic signals that vary from 1 to 10 mm/year and in some locations exceed 30 µm/day.

Table 1 Properties of six-mm-diameter rods used in creepmeters

Material	Thermal Coefficient of linear expansion	cost/m
Invar	0.93-1.0 x 10^{-6}/°C	$10/m
Glass fiber composite	6.5 x 10^{-6}/°C	$7/m
Quartz fiber (Teflon-coated)	8.7 x10^{-6}/°C	$15/m
Quartz fiber composite	-0.64 x10^{-6}/°C	$15/m
Carbon Fiber composite	0.32- 0.65 x 10^{-6}/°C	$17/m

The creepmeters are packaged in a 4 inch diameter PVC pipe terminated by a rubber end cap through which two sealed wires emerge – one to the LVDT and the other to an underwater 12-bit-temperature probe. The entire package is calibrated when assembled and can operate underwater indefinitely. Data are downloaded by removing the rubber cap and an O-ring seal to the data logger, and by inserting a USB cable between it and a

PC equipped with an ONSET download/launch program. Downloading takes roughly 15 minutes from exhumation to internment.

An *Onset* modem is available that permits the data to be accessed from a telephone line or from a remote radio, hence it is possible to turn our creepmeters into real-time telemetry systems for a cost of about $350 and a phone charge of $25/month. We note that this would permit operation of the data logger at a recording rate of one sample per second with automated daily telephone downloads. A complete creepmeter (electronics/LVDT and graphite rod) costs approximately $1200 excluding telemetry. The cost of engineered mounts, however, varies from $2000-$6000, and these were not part of the currently-funded proposal.

Table 2 Coordinates and geometries of micro power creepmeters

Location	lat N	lon E	length	obliquity	depth	material	piers
Ferrum	33.4572	115.8539	10m	30°	30 cm	graphite	2 m s/s
Salt Creek	33.4485	115.8437	8 m	80° (sic)	80 cm	invar wire	2 m pillar
Durmid	33.4147	115.7985	8 m	30°	30 cm	graphite	1.5 m s/s
Superstition Hills	33.72824	116.23171	6 m	30°	30 cm	invar rod	1 m rod
Work Ranch	35.85868	120.39240	30 m	30°	50 cm	invar rod	2 m rod
Nyland	36.85499	121.54628	12 m	45°	30 cm	invar rod	2 m rod
Fremont			30 m	30°	1.2 m	quartz rod	30 m pillar
Palisades			30 m	30°	50 cm	quartz rod	10 m pile
Point Pinole			30 m	30°	2 m	invar rod	10 m pile

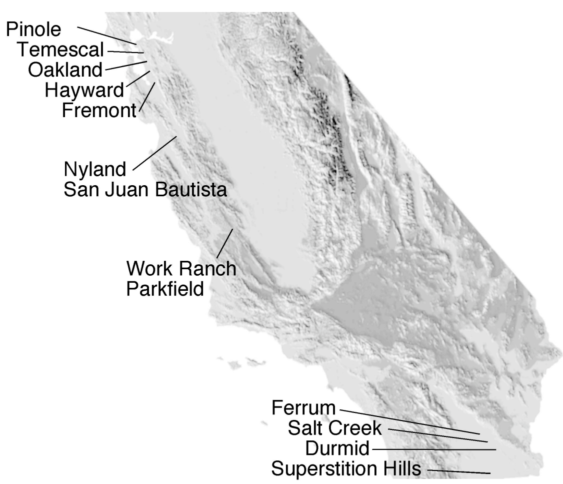


Figure 1. Map of locations of creepmeters discussed in the text.

Coachella Valley Southern California

In our original proposal we promised to revive two creepmeters on the San Andreas fault in the Coachella valley since none have operated south of Parkfield since our funding was terminated a decade ago. One of these was at Indio and the other on the crest of Durmid Hill.   We discovered that a newly constructed golf course had destroyed the Indio site and removed all surface evidence of the fault. Numerous housing developments in the region prevented us from identifying a alternative installation site.

The Durmid creepmeter had corroded completely because of the salts and acid rich soils on Durmid Hill. A new instrument was needed here.

Earlier this year, Dr. Keilis Borok had, on the basis of string theory, predicted a possible earthquake whose potential location included the Coachella Valley. We therefore installed four creepmeters, one at the original Durmid site, the other at the old Caltech creepmeter at Salt Creek, and a third at a new location at Ferrum (see front cover of SRL July 2004). An attempt was made to revive the old North Shore creepmeter initially installed by Caltech but this could not be found because of real-estate development in the region. A fourth creepmeter was installed at the Site 1 point on the Superstition Hills fault.

Table 3: Fieldwork table showing days when crepmeters were visited. Each field visit is described in a 3-10 page report submitted to Menlo Park colleagues. The reports describe voltages, calibrations and mechanical offsets. A preliminary visit was made in 2003 to prepare the proposal. Funding was received in Dec 2003 following which seven field trips were undertaken, with 2-5 day durations. We anticipate that future maintenance will require fewer visits since instruments have now been standardized with autonomous recording systems.

Location	Jul03	Dec03	Dec	Mar04	Mar04	Apr04	Jul04	Aug04
Ferrum				3	24-25	16		26
Salt Creek				3	24	16		26
Durmid				5	24	16		27
Superstition Hills				5	24	16		26
Work Ranch					23	15		
Nyland		8	29		23	15	9	
Fremont	22-24	9-10	27			15	5-6	
Palisades	22	9	27				7	
Point Pinole	22	10	27				7-8	
Temescal	22	12	27				6	
Oakland Zoo	22	12	27				6	

No creep has occurred in the past six months on the Superstition Hills fault. Data from Durmid Hill are shown in Figure 2. The Salt Creek creepmeter was installed by Caltech many years ago at 80° to the fault, a particularly unfavorable azimuth to pick-up dextral slip, but in a direction that renders it very sensitive to fault gouge expansion. It was driven off scale by dessication of the fault zone in June 2004. The instrument responates at 1 second periods and 0.5 mm amplitude during the passage of trains.

Nyland Ranch

This creepmeter is the most northerly on the creeping segment of the San Andreas fault in central California, and is close to the fence that was offset by southernmost slip of the 1906 earthquake. A creepmeter was installed here by Nason in 1960, and operated by us for five years until 1995. We revived the creepmeter in December 2003 with a 12 mm range continuous 6 mA power consumption DC-SE transducer. Between 6 Dec and 22

March the maximum dextral slip at this site measured mechanically was less than 3 mm, consistent with its long term slip rate since 1960 of 7 mm/year.

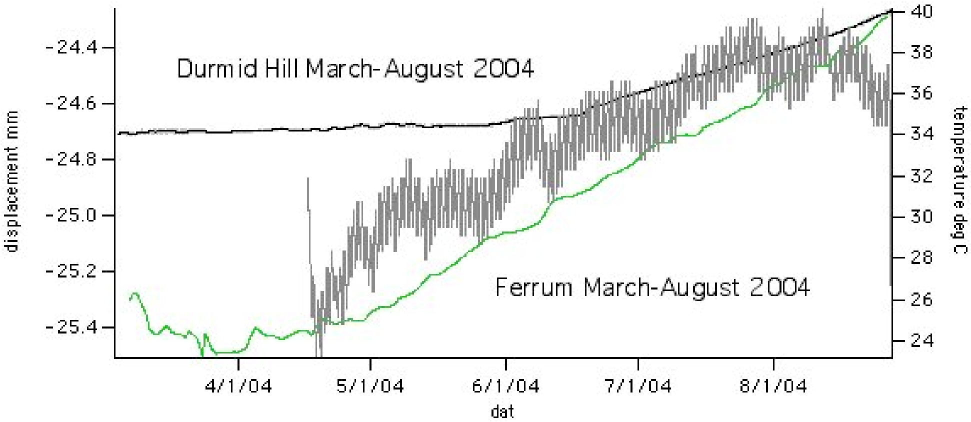


Figure 2. Two minute data samples from two locations on Durmid Hill separated by a distance of 5 km along the San Andreas fault. (Increase displacement by 1.15 to convert to dextral slip. See Table 2 for locations). A creep rate of ≈3 mm/year appears to start in May in Ferrum and in June at Durmid. It is not clear how much of the signal is thermoelastic, however, a 12°C temperature increase occurs that should result in an apparent left-lateral rod contraction of 60 μm at Ferrum and 40 μm at Durmid, whose inclusion would increase the observed rate by 10-15%. The diurnal variation in rod-length caused by the 3°C temperature variation is 1-3 counts (6-18 μm). The data have been processed to suppress this daily signal and are available numerically on the web interpolated to 1 hour samples. The Ferrum data are noisy prior to April since before this time the length-standard was a stainless-steel/invar composite.

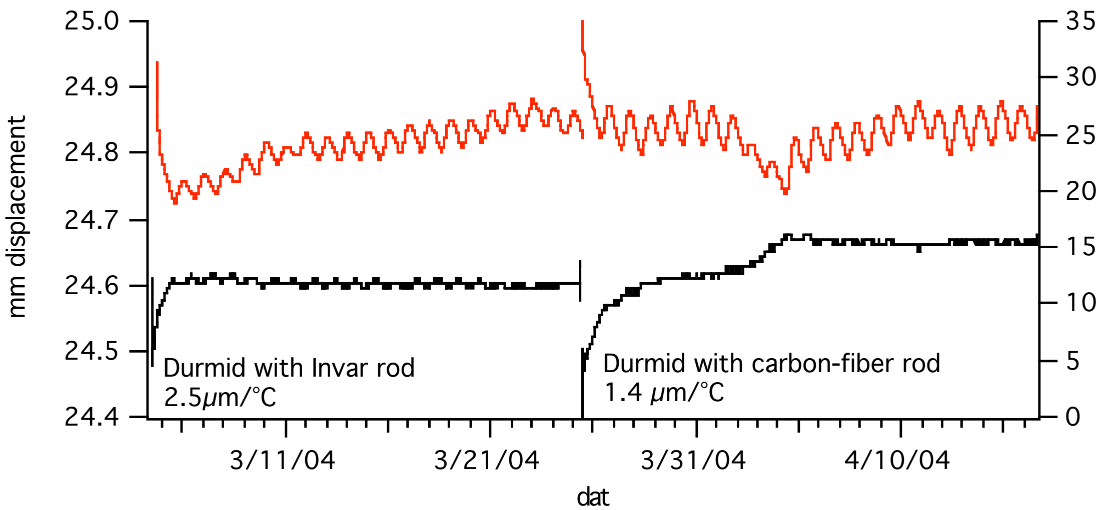


Fig 2B Effect of changing the length standard on Durmid Hill from Invar to graphite. Severe corrosion to the old installation was identified in early March and new stainless-steel rod mounts were driven 25 March which took three days to stabilize.

Experiments Dec 2003-March 2004: In December, we installed the data logger remotely outside the electric fence to facilitate data collection. The 200 mA solar panel, however, was inadequate to keep the battery charged during these winter months and the system lost data. Following the development of the micro power creepmeter described above we decided to scrap this early design and install the first of the new micro power dataloggers there.   However, to retain remote access required wiring the signal leads in-situ, and as it happened, the signal ground of the original 12 mm range DC-SE transducers had been connected to the transducer case at the factory, contrary to specifications. As a result, following this first deployment, we determined that the recorded signal had now been contaminated by ground moisture changes. Following these early problems we decided to abandon the remote recording system in favor of the standardized package described above.   The data logger, power, and transducer are all now operated in the instrument enclosure as a sealed system with no long leads.

March 2004 onward: The San Simeon earthquake was followed a few days later by a slow earthquake in the San Juan Bautista region (Figure 3). The slow earthquake was captured as a creep at the surface with an abrupt 3 mm creep event followed by a slow deceleration over the next few months. By July 2004, 14 mm of creep had occurred, twice the normal annual creep budget. These data are posted on the web both graphically, and as downloadable excel, html and ascii data streams.

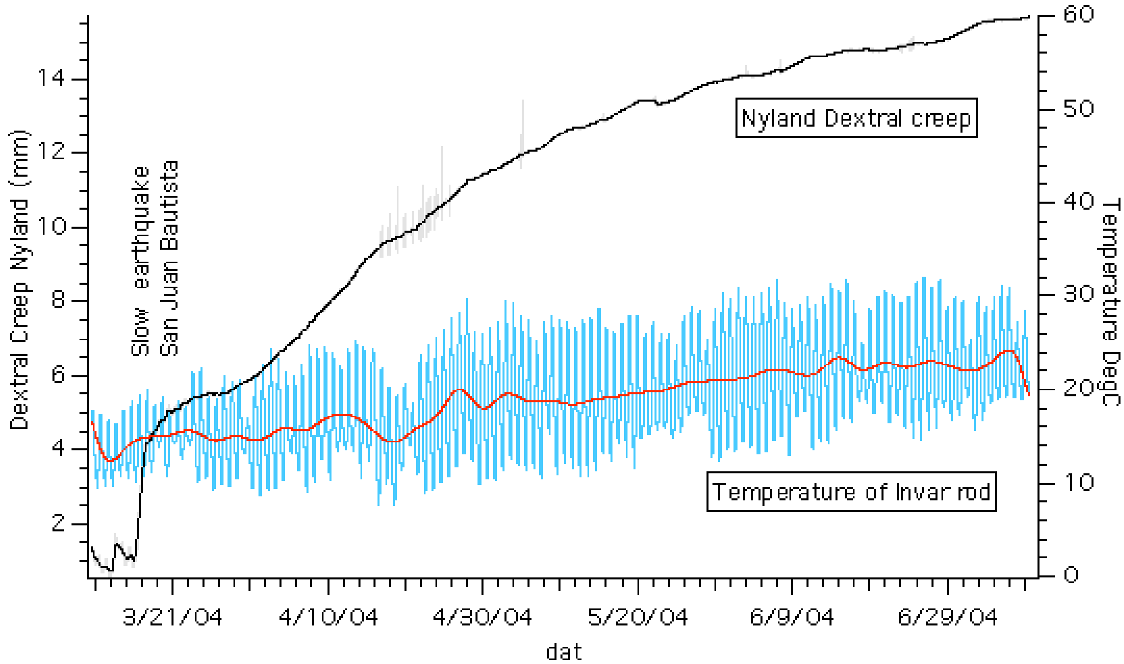


Figure 3 Slow earthquake at Nyland Ranch north of San Juan Bautista. The raw data (grey) have been corrected for non-linear parts of the LVDT output range and have been interpolated to 10 minute values using linear interpolation with pre-averaging and 332 nodes (6 hour nodes=black trace). The temperature data have been interpolated with a cubic-spine filter with 42 nodes (red trace) . The five days at the start and end are filtering artifacts that should be ignored. No temperature correction has been applied to the displacement data, which have been corrected to dextral slip using a 45° obliquity to the fault zone.

Work Ranch, Parkfield: In the past we operated four long range (2 inch) creepmeters in the Parkfield region but these were terminated in 1995. A visit in April 2004 revealed that the Middle Mountain and Highway-46 rods are still in the ground, but the Water Tank creepmeter has been plowed and seeded over. A micro power creepmeter and an extended range creepmeter were installed near the USGS Work Ranch creepmeter in

April 2004, which could, if necessary be hooked into 1 sample per second telephone telemetry. The extended range system records one sample per 10 minutes but has a range of 3 m. No data have yet been retrieved from this site since its installation, although a visit is planned in October.

Hayward fault

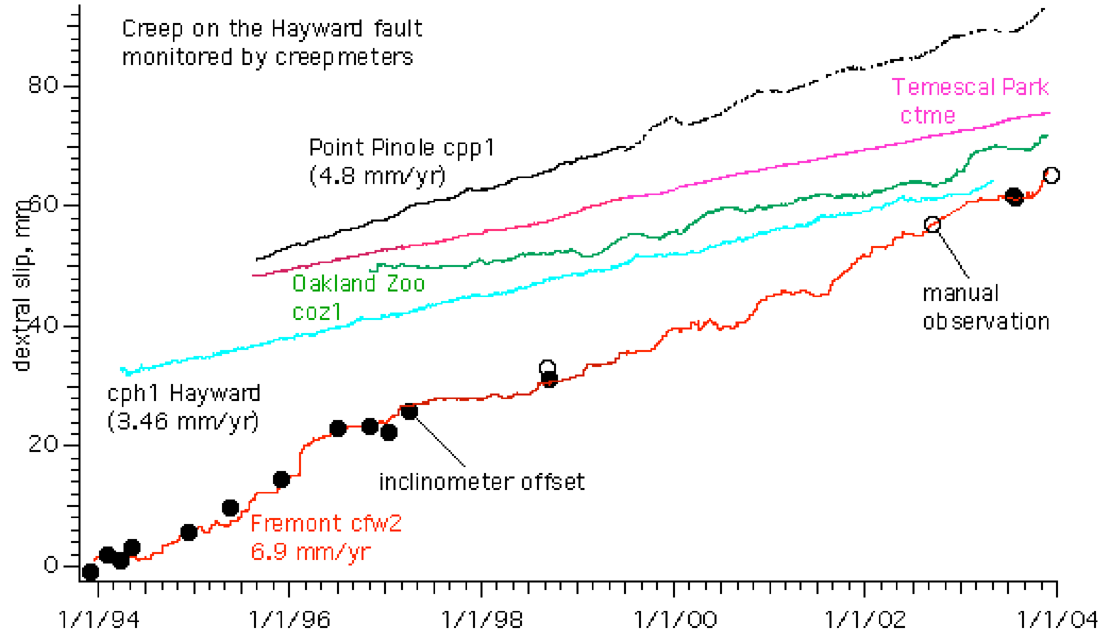
Reports on our visits to the Hayward fault were submitted (Table 3) to our Menlo Park colleagues who share the burden of maintaining power and telemetry to this array of five creepmeters. In December we analyzed the decade of data acquired since installation. A number of problems occurred during the 1998-2003 period when regular funding was unavailable for maintenance, and data acquired during this interval required considerable data editing and interpolation. These edited data are shown in Figure 4 and these will soon concatenated with incoming data and posted on the web graphically and as hourly numeric data.

Point Pinole (cpp1): The geometry of this system was rearranged in 2004 to host a single transducer at its western end. Prior to this time data from a transducer at each end needed to be summed to obtain the creep rate here, an arrangement that caused no stress on the end mounts since the length standard was not dragged through the fault zone by one of the end mounts. The western end, however, flooded regularly and corrosion of the signals there resulted in data loss. The new geometry attaches the creep rod to the western end and monitors the changing displacement at the eastern end as the creep signal.

The creepmeter has a 100 m separation between the fault and the DCP. Power was provided through a pair of ten gauge copper wires and signal through a 3-pair shielded 22 gauge cable. A decade of submersion of the wires below the swamp at Pinole had progressively rendered the data signal unusable. In 2003 only two cables were usable resulting in one of the transducers failing, and the cable failed completely in early July. Four days later we pulled the old cables and replaced them with direct burial multiple-strand irrigation cable. To prevent future loss of data through this undesirable long cable we installed an autonomous micro power data logger that also records temperature near the length standard.

The telemetered data (cpp1) record creep monitored by an invar rod. The autonomous data logger records the data from a fiber glass rod and requires alkaline battery replacement once every two years. The teflon coating was removed from the fiber-glass rod in July since this had been shown to substantially increase its thermal coefficient (Table 1).

Temescal Park (ctmt): This creepmeter normally records a linear creep rate of 5 mm/year derived from three transducers. One records temperature in the form of differential expansion between a galvanized iron tube and an invar rod within it. The other two record creep at high (1 inch range) and low gain (4 inch range). No adjustments to this system have been made in 2004 which shows a similar overall creep rate, but with a slowing in rate in March 04. The creepmeter is often submerged for several weeks each year during the flooding of Temescal Creek.



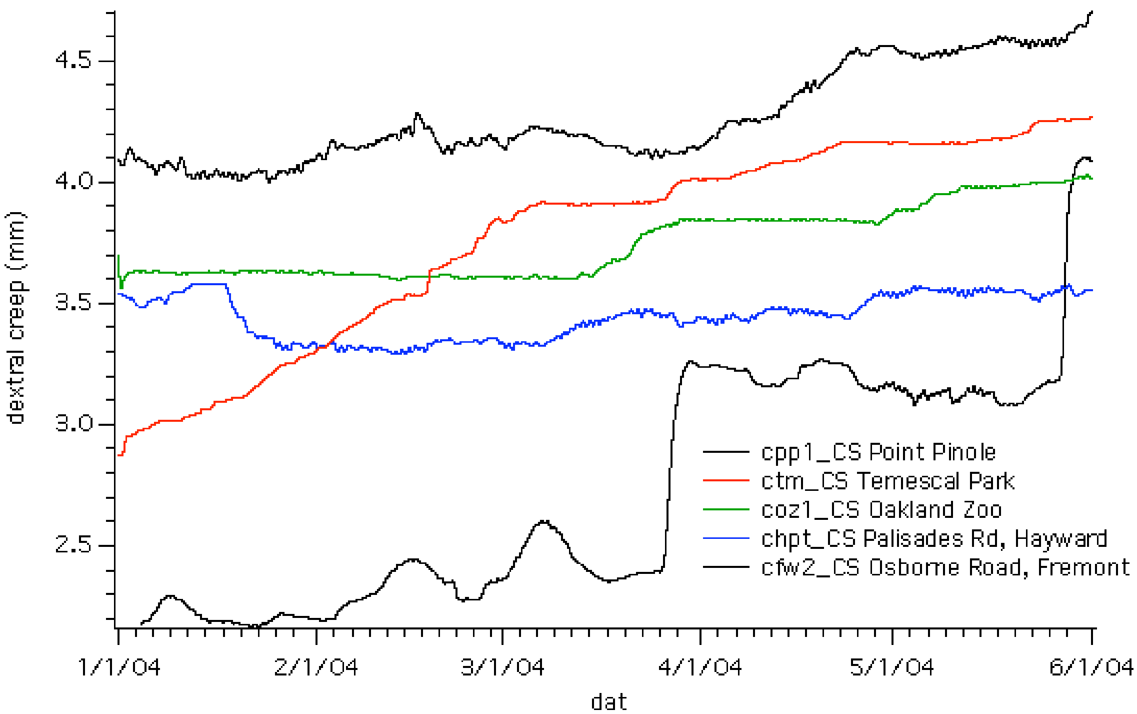


Figure 4 (above) Nine years of data from the Hayward creep array and (below) five months of data since the start of this project in Dec 2003. We plan to merge these data into a continuously updated data stream that can be accessed for any period of time at daily, or hourly resolution. Note 1-4 mm amplitude creep events at Oakland and Fremont are absent elsewhere on the fault. Corroded underground wiring at Point Pinole that was responsible for noise in the data shown in this figure was replaced in July 2004. Evident for the first time in 2004 is a suggestion of a creep acceleration that starts at Palisades and Oakland Zoo in mid April and propagates to the other creepmeters.

Oakland Zoo (coz1): The creepmeter is buried completely by request of the zoo director but will shortly require mechanical adjustment since one of the two transducers is close to the end of its range. Power to the system failed in early 2004 but this was fixed following a visit by Vince Keller.

Data from Oakland Zoo are of interest in that they show small creep events. These 2-3 mm amplitude events (28 Sept 02 and July 04) are accompanied by nearby strain changes and microseismicity. Data for these events have been posted on the web. The most recent are shown in Figure 5,

Palisades Road Hayward (*chp1*). This creepmeter is the only one of the Hayward array that upgraded an existing creepmeter originally installed by Nason. It crosses Palisades road at shallow depth and at 45° to the fault, an unfortunate combination that results in high thermoelastic noise at diurnal and annual periods. Transmissions from the creepmeter became unreliable in early 2004 caused partly by DCP errors and partly by a fault in the power to the transducers. In an attempt to improve the reliability and quality of data from this site we stripped the teflon from the length standard, removed a magnetostrictive transducer, and installed an autonomous micro power system as a back-up. The data continue to be dominated by a large diurnal thermoelastic signal, which we are attempting to develop a predictive filter for its real time suppression. The data from *chp1* sample only 80% of the creep signal here because the fault zone is more than 100 m wide.

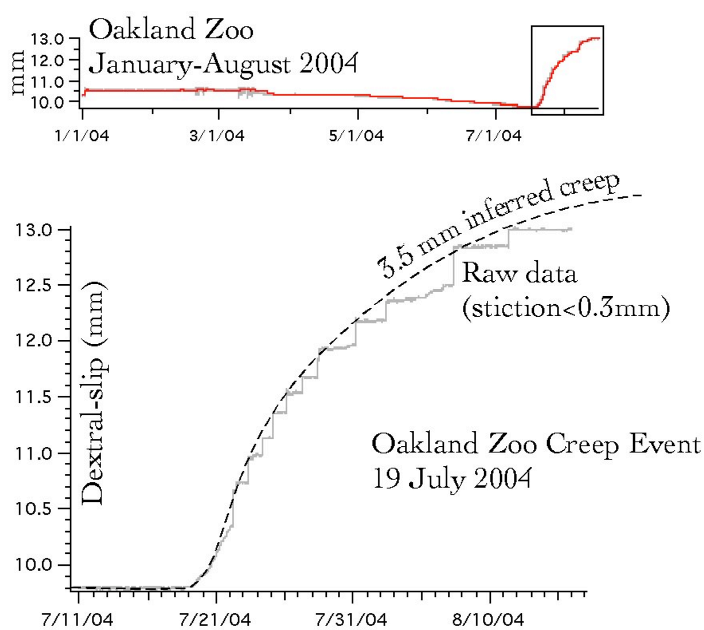


Figure 5 An unusually large creep event at Oakland Zoo interrupts a thermoelastic contraction that characterizes the coz1 data for the preceding 7 months. The instrument has not been exhumed for 8 years and exhibits stick slip behavior at the 0.4 mm level, we plan to reduce this stiction in the fall of 2004. The creep event was accompanied by microseismicity on the Hayward fault (see http://cires.colorado.edu/~bilham/ZooCreepEvents.htm).

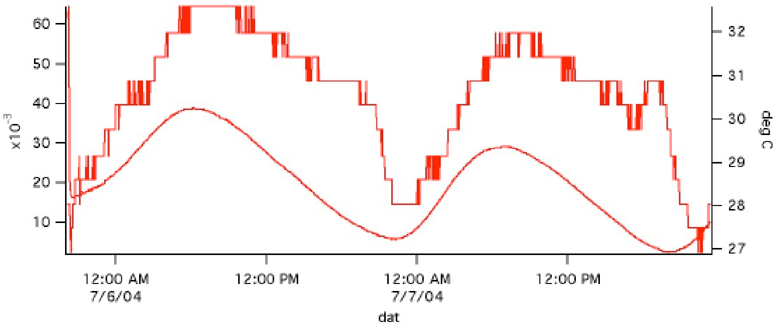


Figure 6 Half-mm diurnal thermoelastic signal at Palisades Road, Hayward (chp1) and 5°C daily variation at 30 cm depth. (6 µm digitization evident in the displacement signal). Note that a linear filter would only partially suppress this signal.

Osgood Road, Fremont (*cfw1, cfw2*)

The solar panels here had by late 2003 aged to the point that they could no longer power the original three transducers. Power to *cfw1* and *cfwt* transducers were terminated and these channels are no longer transmitted. Instead a micro power system was introduced to record these signals. Initial data from this arrangement are shown in Fig. 7.

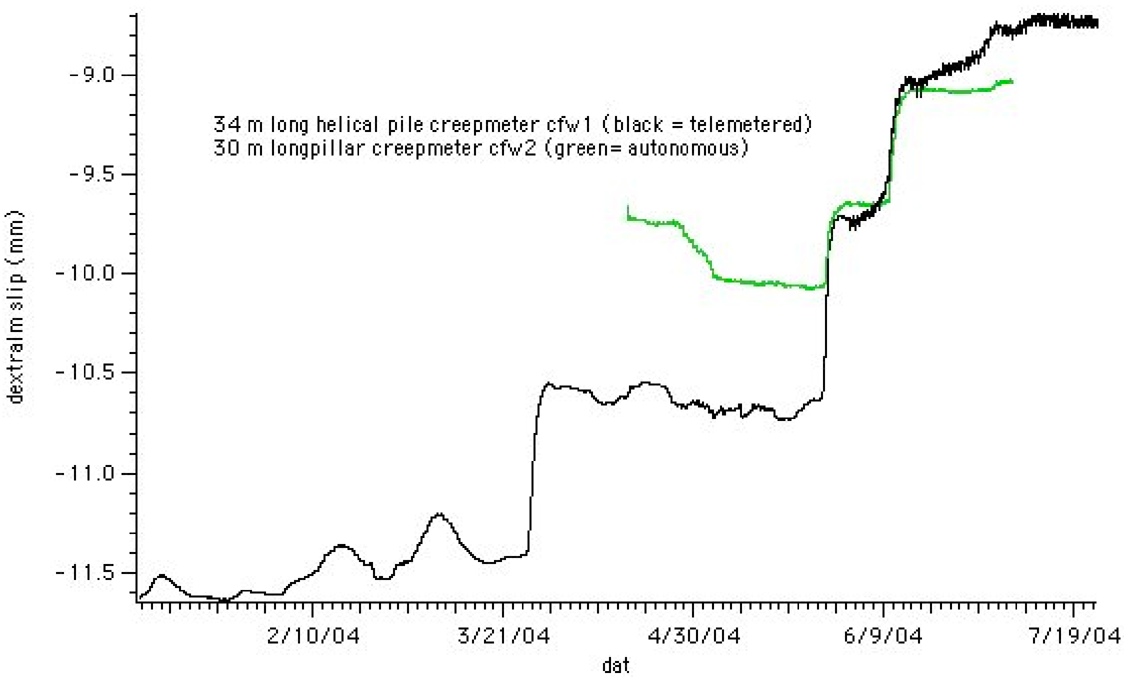


Figure 7. Processed data from the new data logger (March-July) are shown in green above. The black trace represents the transmitted data (January-July). Three ≈1 mm amplitude creep events are superimposed on noise probably related to soil moisture. The two creepmeters are coaxial but use different mounts and record a different response to the events. The shorter trace comes from the micro power creepmeter (glass fiber) which is 4 m shorter than the (invar) telemetered creepmeter, and whose data must be downloaded manually. A wedge of material in the top 10 m of the fault zone is believed to be responsible for the different signals.

Mammoth Lakes tiltmeter

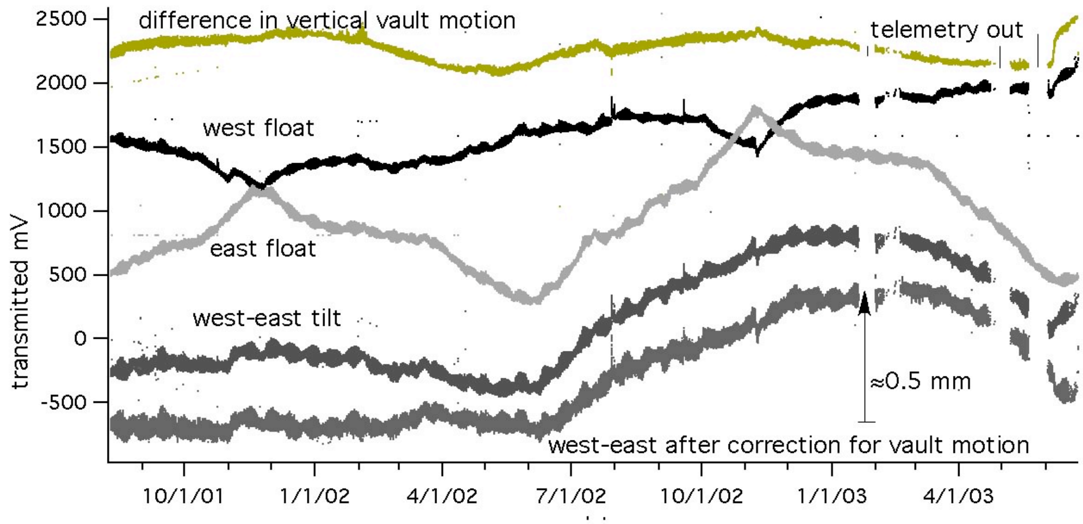


Figure 8 Data from the long Valley biaxial tiltmeter illustrating an inflation episode that occurred before transmission failure in 2003. The lowest two traces indicates the east-west tilt signal before and after correcting for vertical vault motions at each end.

The biaxial tiltmeter at Long Valley uses a float system that maintains its datum during power outages or transmission failures (http://cires.colorado.edu/~bilham/tiltmeter.file/Tiltmeters.html. It has operated for 15 years but telemetry failed in 2003. Following the repair of the DCP in 2004, processing of the data has recommenced and is now being automated. We have received no funds to undertake this specifically, so that it remains as a low priority. The instrument has not been visited for about two years. The figure shows an inflation event of 2002 prior to the telemetry failure.

Personnel

Laboratory investigations of creepmeter and rupture meter performance were undertaken by Naia Suszek (Graduate student) and Sean Pinkney (undergraduate). A web page initiated by Suba Periakaruppan (graduate student) has been improved and automated by Dr. Susanna Gross. Field installation and maintenance of the California creepmeters has been undertaken by the PI.

Plans

The PI will be visiting Berkeley for two months in October-November 2004 and plans to unify the creepmeters to facilitate future maintenance. Rewiring is badly needed to simplify maintenance and a printed-circuit junction board is planned for each of the creepmeters. The board has been designed with the potential to attach 3 transducers neatly to the DCP cabling, with an onboard temperature sensor and power regulator. The board fits within a three-inch waterproof PVC pipe terminated by rubber end caps, and has test points on all output and power lines.

Delrin ball races and an autonomous data logger will be added to the Oakland Zoo creepmeter, and a data logger added to the Temescal creepmeter. A low power 4 inch range LVDT will be added to the Palisades creepmeter to bring its low gain range into line with the four other sites. If funds permit, a tiltmeter will be installed in the inclinometer shaft at Fremont, following the repair of inclinometer torpedo that sprung a leak in 2003.

A paper summarising the past decade of creep on the Hayward fault is in preparation for publication in 2005.

Results

1. We have corrected several instrumental malfunctions that developed during a period when no funding was available to maintain the Hayward creepmeter array 1998-2003. All five instruments are now functioning smoothly.
2. We designed and tested two new micro-power creepmeters (Bilham et al, 2004) that can operate continuously for a year: a creepmeter with 6 μm resolution, 32 mm range and 2 minute sampling interval, and a rupture-meter with 1 mm resolution, 3 m range and 10 minute sampling interval. Both units operate from disposable alkaline cells. The creepmeter can operate continuously underwater.
3. We have added backup creepmeter recording systems to three of the five Hayward creepmeters to overcome local power failures and DCP outages, and have installed six additional creepmeters in central and southern California.
4. We have developed an online data display that permits data to be recovered for any time period **http://strike~sjg/creep** . At the time of writing the site provides raw data corrected for calibration and transmission glitches. We plan to modify this to include processed data corrected for thermal and thermoelastic signals.
5. We re-started five additional creepmeters on the San Andreas fault and one on the Superstition Hills fault. We have posted incoming data from the Coachella Valley and Nyland Ranch creepmeters as graphic charts and as ascii or excel data.
6. We captured a slow earthquake from the northernmost creeping section of the San Andreas fault, following the San Simeon earthquake. http://cires.colorado.edu/~bilham/creepmeter.file/Nyland_11-23_March.htm
7. We captured a creep-event at Oakland Zoo in July, the second event in a decade of meaurement that was associated with microseismicity on the Hayward fault in the region (http://cires.colorado.edu/~bilham/ZooCreepEvents.htm).
8. We have started an analysis of Long Valley tiltmeter data and hope to develop this into a similar form to that which now permits access to creep data.
9. We published an article summarizing the above developments, and prepared two technical notes released as design applications by *ONSET* and *LUCAS*/*SCHAEVITZ* corporations.

Non-technical Summary:

Creep, or slow surface slip occurs on several faults in California at rates of up to 1/2" each year, either steadily, or episodically following intervals of inactivity. This slip breaks pipes and cables in urban areas, and tends to reduce the slip available to drive earthquakes, either delaying rupture or reducing the size of a future earthquake. The project measures creep rates at five locations in the Bay Area and at six locations on the San Andreas system to the south. Abrupt changes in rate may herald future seismicity. Long term creep rates permit seismic hazards to be refined.

Reports published

Bilham, Roger, Naia Suszek, and Sean Pinkney, (2004) California Creepmeters, *Seismological Research Letters,* **75(4)**, 481-492.

Technical Application Notes: http://cires.colorado.edu/~bilham/creepmeter.file/creepmeters.htm
Bilham, R., (2004) A micro power fault slip meter with 3-m range using an Onset U12 data logger or an Onset Microstation data logger
Bilham R., (2004) A micro power creepmeter based on a Schaevitz DC-SE LVDT.

Data Availability

The data are currently available as ascii column text or excel files as 1 hour samples, or as 1 minute, ten minute or five minute IGOR wave files. They include temperature data. Post 2004 data are now available on a creepmeter web page that permits any period of data to be sampled and downloaded or displayed.

Data can be dowloaded from
http://cires.colorado.edu/~bilham/
or from
http://strike~sjg/creep

Contact Roger Bilham (303 492 6189 bilham@colorado.edu) or Susanna Gross for earlier data that are not yet accessible on the world-wide web